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PARABOLOIDAL THIN FILM INFLATABLE CONCENTRATORS AND THEIR USE FOR POWER APPLICATIONS

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ABSTRACT

This paper deals with a proposal to use thin film inflatable concentrators, currently used for propulsion, in other applications, such as power. Technology for precision paraboloidal thin film concentrators is becoming available for use as a byproduct of propulsion technology. The idea is to introduce the possibility of using this formerly strictly propulsion hardware to power photovoltaic (PV) cells. Several intensity profiles will be generated from an optical model and shown for thin film inflatable concentrators.

INTRODUCTION

Inflatable technology for antennas and solar concentrators is rapidly maturing. Large inflatable paraboloids, developed for space propulsion systems and antennas, are now available for ground test of power systems. This paper reviews past work on inflatable antennas and structures. It then proposes testing of a photovoltaic array using a 5-meter inflatable paraboloid antenna that is currently available. The RF reflective coating on this antenna will also reflect sunlight so it can also be used as a solar concentrator. Some preliminary calculations are performed to give an idea of how such a test should be set up.

Inflatable structures can potentially reduce spacecraft weight and decrease the volume required by a power system. Reflective surfaces do not require much mass so that inflatable antennas or concentrators can be very lightweight. Inflatables can also be packaged more compactly than rigid structures thereby reducing volume constraints in a faring. Therefore, we believe that space power applications could benefit from this technology.

THE NEED FOR PRECISION INFLATABLE PARABOLOIDS - In 1959, a company named L'Garde (an acronym formed from the first letters in the six cofounder's names), began building and testing thin (plastic-like) film inflatable antennas for space. These first inflatables were flown as the Echo I and II; PAGEOS; and Explorer 9 and 10. Those flight tests were mostly successful, and their application adequately demonstrated the reflection of radio signals. In general, inflatable systems required less stowage volume, were lighter in weight, and were less expensive to develop and produce than precision rigid or mesh deployable systems. This still holds true today. Figure 1 is a graph of stowage volume versus antenna size (diameter). CFE (Critical Flight Experiment) is a 4 x 6 meter concentrator (with a 4 meter diameter collection area) being built for the Solar Orbit Transfer Vehicle (SOTV). IAE was a 13 meter diameter antenna flown in 1996 from the space shuttle. IAE did not completely deploy, unfortunately. The ASTRO Mesh antenna is an example of a rigid deployable antenna. A line is plotted to show anticipated ASTRO Mesh volume versus diameter. Imaging optical applications with conventional mirrors will require even greater volumes that are off this chart. Figure 2 shows a deflated 4.88 meter diameter inflatable antenna in preparation for packaging.

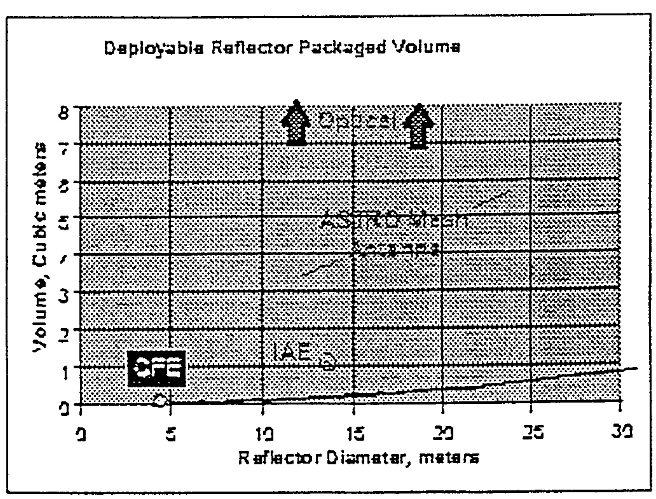

Figure 1. Deployable Thin Film Inflatable Packaged Volume Graph

Antennas for terrestrial and space applications mimic solar thermal propulsion concentrators almost exactly; be they precision, mesh deployable, or inflatable. See Figure 3. They use paraboloid shapes and may reflect and focus radiant energy. They differ in that antennas must focus coherently and solar concentrators do not need to. The 4.88-m diameter thin film inflatable antenna is shown in the Solar Laboratory Facility at Edwards AFB CA. The structure in the foreground of the picture is the heliostat, used to track the sun and shine the parallel rays into the concentrator or antenna as the case may be.

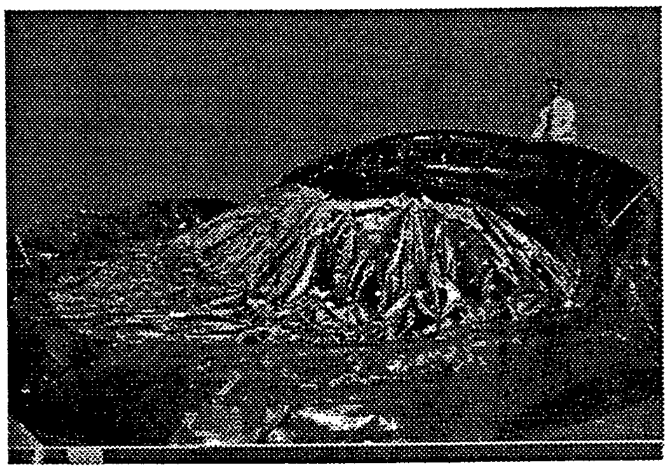

Figure 2. Thin Film Inflatable Being Packaged

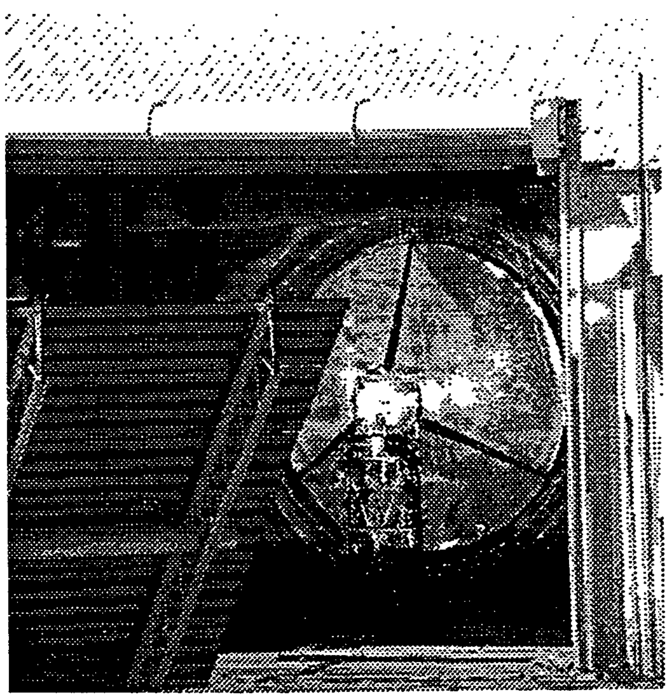

Figure 3. Sunlit 4.1-m Diameter Thin Film Inflatable Antenna in Solar Lab

CONCENTRATORS - All concentrators, both on- and off-axis, are geometrically generated from a right circular cone. A parabola is inscribed within the cone and revolved to become a parabolic concentrator. If an on-axis paraboloid is required, the circular area symmetric about the axis of rotation is used. Primary off-axis concentrators used for solar thermal propulsion are taken from a cone axis away from the axis of rotation. This is done for a specific reason. See Figure 4, the off-axis parabola geometry schematic. Note the on-axis paraboloid curve, the dashed line, and the vertical line passing through the bottom of the "bowl". If a thruster were close to the bottom of the "bowl" near the paraboloid focus, and if it needed to collect sunlight from any angle while the rocket needed to move in any other direction, there would be some combinations where the sunlight would be blocked by the bottom of the paraboloid. Specifically, the rocket might block the sunlight if it were directly in front of or directly behind the direction of travel. Also, if the sun were directly in the path of the direction of travel, the exhaust plume might impinge upon the concentrator, degrading it.

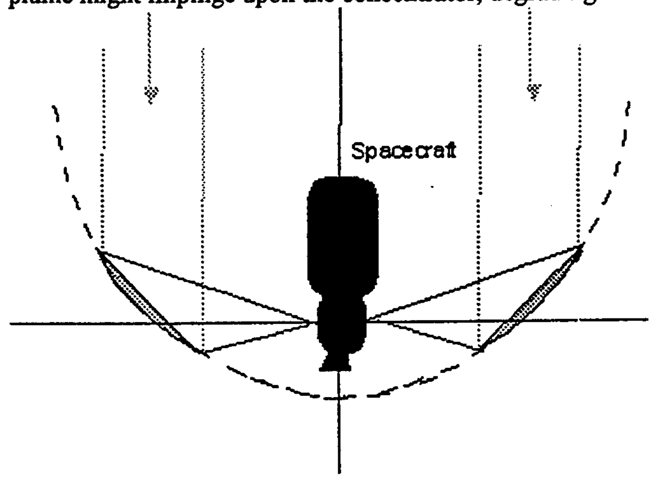

Figure 4. Off-Axis Parabola Geometry

The possible blocking and impingement was construed as a problem. The solution was to take two elliptical sections of the paraboloid away from the axis of symmetry (off-axis paraboloids). As it works out, the intersection of the cone surface with the paraboloid of revolution is an ellipse. See Figure 5, one half of a concentrator system. When looking into the full face of the concentrator, perpendicular to the major axis, one would see an ellipse. What the focus "sees" is a circle, because the sun comes in at the half angle, θ_c, formed between the concentrator plane and the focus. An observer standing on the sun would see the edge of the concentrator as a circle.

An on-axis parabola would look circular viewed from both surface and focus. Concentrators used for solar thermal rocket propulsion applications are typically very precise and accurate in shape. The required geometric concentration ratio, that is, the area of the primary concentrator based on the projected diameter divided by the focus diameter, is higher for solar thermal propulsion than for solar power generation, or solar power dynamics systems. The desired concentration ratio for solar thermal propulsion is 10,000:1. That means the surface accuracy error needs to be about 1 mm RMS or less, and the slope accuracy error needs to be about 2 mrad RMS or less, to meet that concentration ratio goal. For antennas, the required surface accuracy is about 1/20 λ, or about 1.0 mm for 15 GHz. This is about the precision need for solar-thermal propulsion.

For photovoltaic solar power generation, trough concentrators can be used. The trough sides are made up of two flat thin film mirrors reflecting sunlight on a flat photovoltaic panel in the bottom of the trough. The concentration ratio approaches 2 in this case. Flatness within fractions of a millimeter of the thin film is important, as it is very important to have uniform light on photovoltaic cells. For solar power dynamics, where the concentrated sunlight is trained on a cycle engine, like a Stirling, Brayton, Rankine engine, etc., the required concentration ratio is approximately 200-500:1.

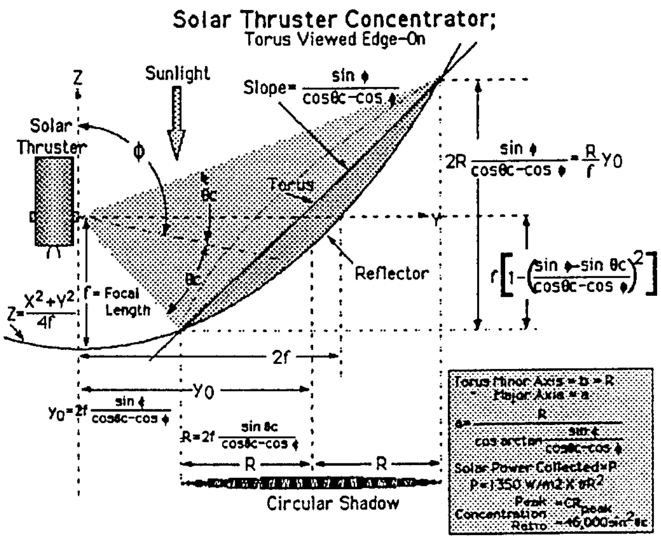

Figure 5. Off-Axis Concentrator Configuration, Viewed Edge-On

<u>ASTEC</u> – The first thin film solar concentrator was called the Advanced Solar Technology Electric Concept (ASTEC) solar concentrator and was built by Sundstrand/Goodyear Corporation in 1964. This was a sub-scale concentrator and is shown in Figure 6. It was produced by cutting flat gores from 1-mil thick mylar, then seaming them together to form a curved surface, and taping the edges together. Curved concentrator surfaces can be made from flat gores in the same way that flat projections of the globe can be reassembled to make a sphere. If enough flat projected segments, or gores, are used then the desired curved surface can be accurately produced.

The backside of the ASTEC concentrator was sprayed with a lacquer coating and polyurethane foam. The ultimate 44.5 foot diameter mirror design was to be supported by a tubular truss system. The estimated peak concentration ratio was 3200:1. The foaming technique produced what is known as print-through, a problem that produces an orange peel look to the mirror surface that reduces its performance.

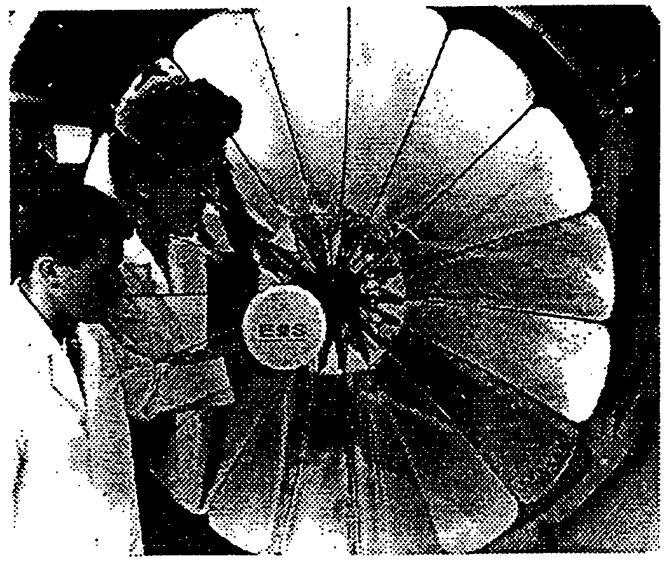

Figure 6. Sundstrand/Goodyear Corporation ASTEC

Thin film inflatable concentrators consist of a reflector and a canopy joined to form a lenticular configuration. The canopy is a clear material that allows the solar energy to pass through, but holds inflation gas in. The reflector film is a reflectorized canopy film. Using two films of the same shape balances forces within the edge of the lenticular and support torus. Thin film inflatable concentrator work started about 1983. The two primary contractors involved in making them used the same method. Since then, more contractors are making concentrators, and many more methods have been tried with varying degrees of success.

<u>L'Garde Seamed and Gored Concentrators</u> – L'Garde constructed a reflector and canopy with many gores joined together by heat sensitive adhesive tape. See Figure 7. The 3-m reflector in this program, tested without the canopy (vacuum backed instead of inflated) achieved a combination of 1.5 mrad random and 2.8 mrad systematic slope accuracy error (3.175 mrad RMS); greatly reducing the complexity and cost of making thin film seamed and gored concentrators. This equated to about 12,000:1 concentration ratio, according to L'Garde.

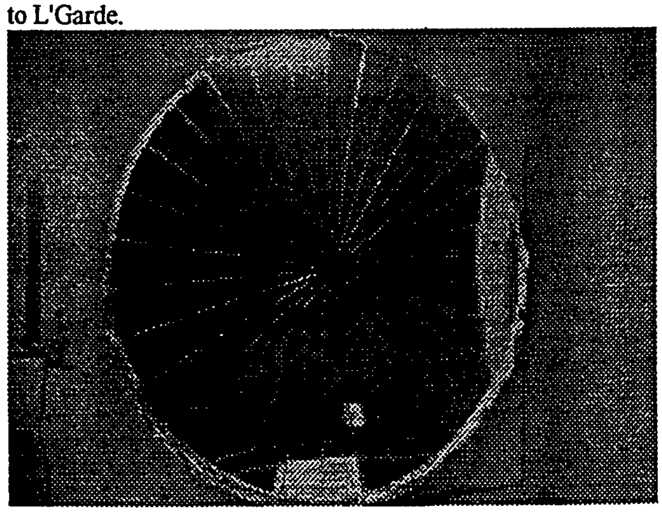

Figure 7. Picture of Highly Accurate Inflatable Reflector 3-m Test

For this project, the reflector was fabricated of Kapton film with vapor deposited aluminum (VDA) as the mirror finish. L'Garde selected Kapton because of its high strength and space proven characteristics. The VDA covered both surfaces of the Kapton reflector, protecting the Kapton from atomic oxygen degradation. Teflon™ film could be used for the canopy instead of Kapton because of its high transmissivity. By late 1990, a large 7-m x 9-m off-axis parabolic reflector was produced using the same method, seaming flat gore segments together. The accuracy of the large off-axis parabolic reflector was not proportionally as good as that of the 3-m on-axis concentrator.

<u>L'Garde Rigidized Concentrators</u> - The idea of rigidizing inflatable concentrators came about because of the fear of micro meteoroid and space debris punctures letting the inflatant gas out of the lenticular concentrator. Removing the canopy and its transmission losses also makes rigidization desirable. There were fears that micrometeoroids would tear out more material than the size of the micrometeoroid because of elastic strain energies in the film. NASA led the way in the early 1960's to 1970's with self-rigidizing systems to the point where inflation was used mainly as a forming or erection mechanism. However, this caused the weight of solar thermal propulsion systems to increase with increasing rigidization.

L'Garde rigidized thin film reflectors by using a thin laminate of mylar/aluminum/mylar composite formed into a lenticular that was deployed by inflation. This material was stiff enough that once deployed it would maintain its shape. The resulting thin smooth shell structure did not require internal pressure for strength. This type of structure is capable of carrying up to 50-pound loads in compression.

<u>SRS Technologies Seamed and Gored Concentrators</u> -Very large, accurate reflectors are needed for solar thermal rocket propulsion systems and like L'Garde, SRS approached the problem with seaming and goring. A key step in their plan was to identify materials, methods, designs, and control techniques to enable construction of thin film membranes in sizes up to a few meters in diameter; and improve upon the current surface accuracy of concentrators. SRS Technologies also investigated new methods of joining flat film segments to simulate curved surfaces. See Figure 8. As will be seen later, their materials research led them away from seaming and goring of flat segments. They also looked at ways to measure surface accuracy, such as laser ray trace and calorimetry methods.

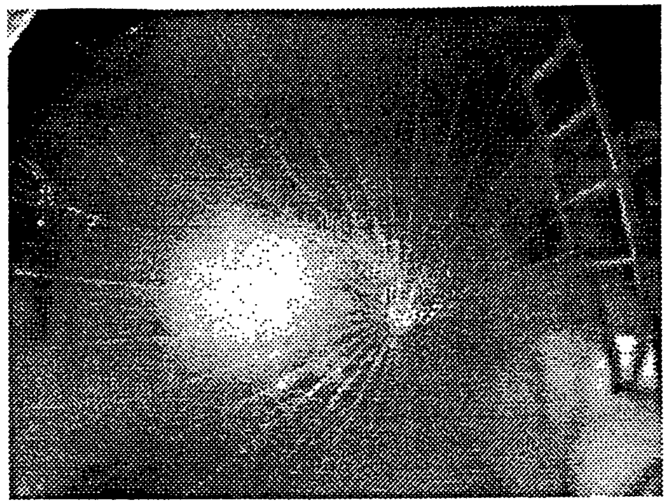

Figure 8. SRS Seamed and Gored On-Axis Concentrator

<u>Electro-Statically Controlled</u> - Then SRS applied Coulomb's Law techniques to shape a concentrator electro-statically. Charge was distributed behind the reflective film on an array of conductors. The shape could be changed by charging different conductors to the desired level with respect to the reflective film. See Figure 9. SRS built prototype models to prove their ideas. In the end feasibility of the new techniques was demonstrated [1]. On the left hand side is the uncharged reflector, and on the right, charge has been introduced. The method worked very well for on-axis concentrators, but not so well for off-axis concentrators which tended to wrinkle, presumably because the off-axis paraboloids are unsymmetrical. This work was performed under a phase I SBIR and was not pursued further.

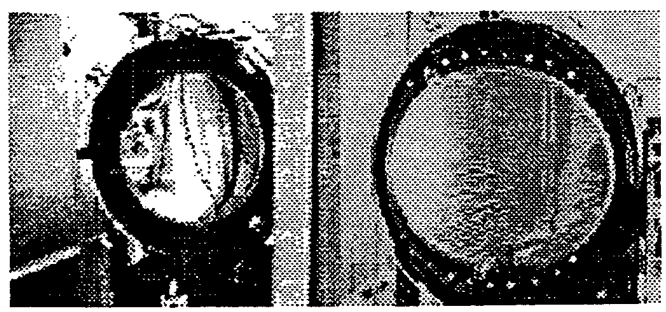

Figure 9. Electro-statically Controlled Concentrator

<u>Creep-Formed Concentrators</u> - In 1989, SRS Technologies attempted to improve overall shape by getting rid of flat gores and replacing them with more accurate curved gores. SRS Technologies demonstrated the feasibility of creep-forming thin aluminized film using iterative procedures to produce off-axis paraboloid geometries. SRS gained valuable insight into the process by which Kapton creeps under uniaxial loads near the yield stress. Creep forming is based on the visco-elastic behavior of polymers in which a time-dependent deformation occurs under a constant load at an elevated temperature. SRS evaluated the creep behavior of 0.3 mil and thicker metallized polyimide film and defined the processing parameters for large-scale creep forming which would be necessary for operational-size solar concentrators. This

approach was ultimately limited by the lack of homogeneity of off-the-shelf films and materials. This led SRS to start producing their own film materials, which in turn led them to form the film directly to the desired shape as seen below.

Seamless and Goreless Concentrators - In 1991, SRS Technologies first began efforts to remove seams and the resultant perceived errors. The objective was to determine whether a pre-shaped metallized thin film reflector surface, which closely approximates the desired geometry, could greatly facilitate accurate surface control, and 2) to find a way to dispense with seams altogether. At this time, SRS concluded that operational reflector systems would still require some film seaming to meet the reflecting surface area requirements.

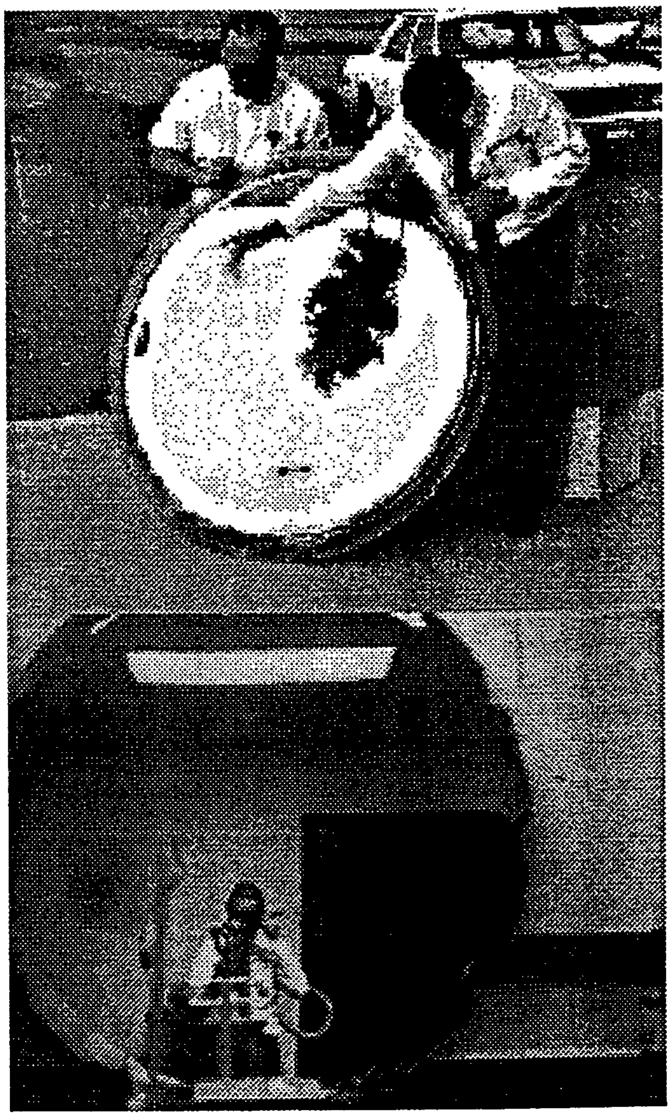

Figure 10. Seamless and Goreless Spin-Cast Reflector

One method to produce seamless, goreless reflectors, possibly up to 33 m in diameter, involves spinning the liquid polymer on a flat plate. The liquid spreads with varying thickness depending on its viscosity, the duration of spinning and on the angular speed. The film was then cured once the designed thickness profile was produced. The correct shape could be obtained by inflating to a pressure specific to the film thickness profile. This pressure combined with the thickness profile induced the proper film strain to produce the desired curvature. In this way, the theory went, a paraboloid curvature could be produced from a flat varying thickness film with only inflation pressure. In addition, a silvering technique that allows large reflectors to be prepared in parts with no demarcations between old silvering and new silvering deposits was used on this concentrator. See Figure 10. The techniques for spin casting and silvering are completely reversible; possibly enabling reflectors to be recycled [2].

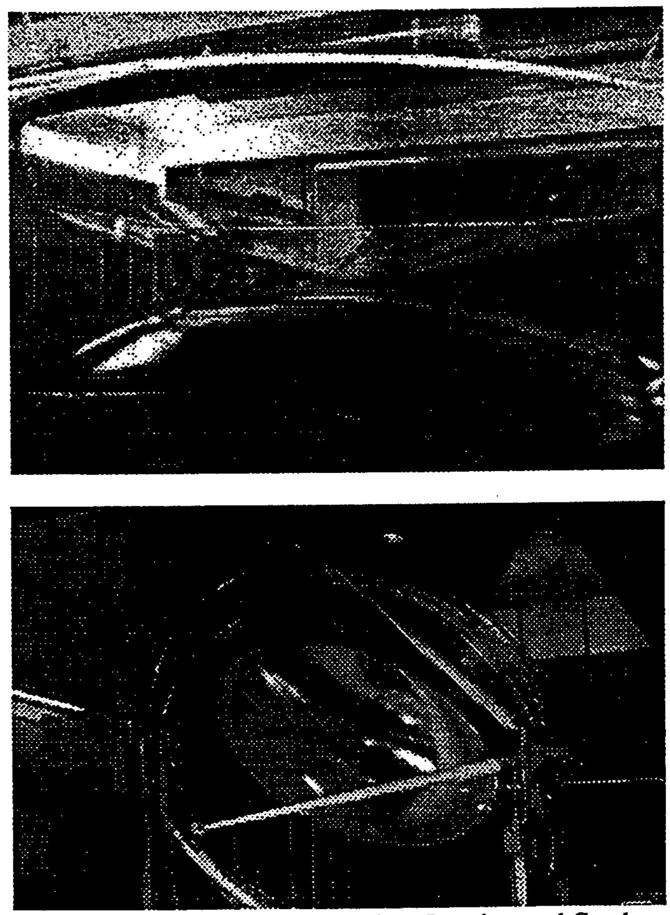

Figure 11. Mandrel and Mandrel Cast Seamless and Goreless Concentrator

SRS's seamless fabrication efforts have culminated in a casting technique they developed. In this approach, the films are formed in the desired shape on a mold or mandrel. This approach turned out to be simpler and worked better than creep forming or spin casting. The results of material testing led to the selection of NASA Langley polyimide film as opposed to commercially available polyimides. The characterization testing of commercially available films revealed that the material properties of the films varied from batch to batch and varied in thickness. The NASA polyimides are available in solution form and can be cast on parabolic shapes to form the desired concentrator shape. See Figure 11. The use of polyimide films in solution form is a

dramatic step in being able to control the fabricated shape and on-orbit configuration of inflated parabolic shaped concentrators.
Furthermore, initial measurements indicate that these films are relatively resistant to space environment degradation.

Foam Inflated and Rigidized Concentrators - An early way of rigidizing concentrators involved fabricating the reflector from three nested thin film membranes instead of two. The canopy membrane existed, as before, the reflective membrane is the same as it was, and inflatant gas fills the space between the two. The third membrane was placed on the back of the reflective membrane. Then, between the reflector and the third membrane solvent swelled foam is injected and cured, leaving a hard shell impervious to dynamic loads, and resistant to micrometeoroids. See Figure 12. Unfortunately, the method, foam inflation rigidization, did not work very well for rigidizing concentrators. It was difficult to flow the foam, which is inherently viscous, evenly into the gap between the films. This is because the thickness of the gap varied greatly between the perimeter and the center of the concentrator.

Foam Rigidized Concentrator - Driven by deficiencies in the double chamber approach, SRS Technologies found a new way to design and easily fabricate spray-foam-rigidized solar concentrators. Only two membranes, the canopy and reflector, are used for this method, reverting to a simpler design for this technique. The method is similar to sputtering aluminum in a vacuum chamber (a Space Environment Facility-SPEF Chamber was used). The idea is that anything (aluminum or foam) will agglomerate onto the first cold surface in a direct line of sight of the spray in vacuum. After curing was complete, the canopy might then be removed, leaving a hard, rigid shell, and allowing up to 30% more flux into the thruster because the sunlight would not have to transmit through the canopy twice on its way into the aperture. See Figures 13 and 14.

Figure 12. Foam Inflated and Rigidized Concentrator

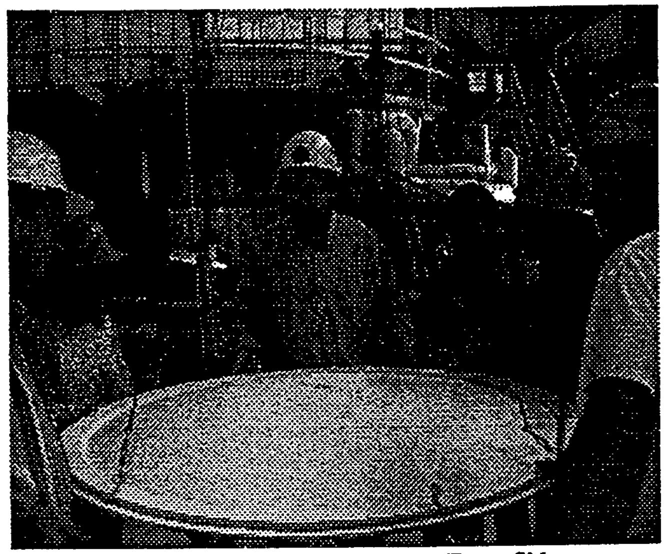

Figure 13. Foam Rigidized Concentrator Foam Side

PERFORMANCE OF 2M x 3M SRS TECHNOLOGIES CONCENTRATOR

SRS Technologies has produced a series of 2x3 meter off-axis concentrators. This set of inflatable concentrators was the first to be thoroughly tested for solar-thermal propulsion. The first of these achieved about 3.5 milliradians RMS slope error [3]. The transmission of the canopy on this early concentrator was fairly low, however, subsequent improvements have raised transmission to about 63 percent, which is close to the theoretical maximum possible given reflection losses at the canopy. Absorption losses are very small. The resulting peak intensity, given these parameters, is about 800 watts/cm^2.

Improvements on slope error have also been made but this will have little effect on the applications discussed here.
The 2x3-meter off-axis concentrator was originally built as a scale proof of concept article for solar thermal propulsion. As such, the requirements for surface accuracy were fairly demanding, as mentioned earlier.

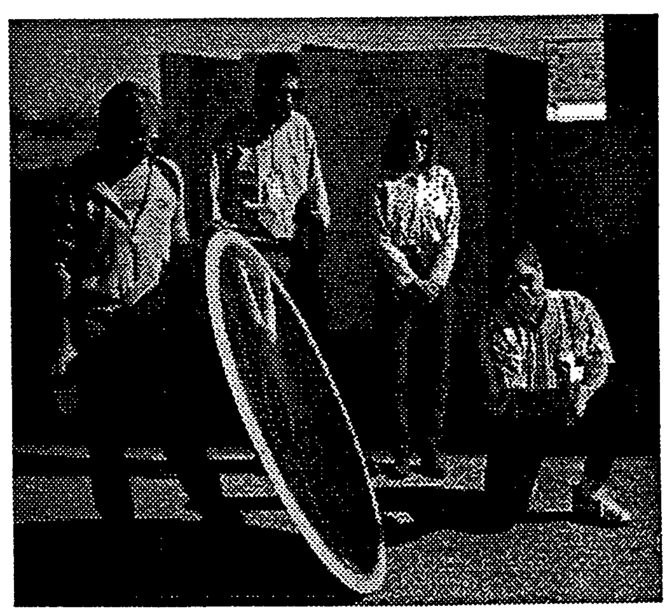

Figure 14. Foam Rigidized Reflector

SRS Technologies has also produced a 5-m inflatable antenna that could be used for power applications. This antenna was produced using the same techniques as their 2x3-m off-axis concentrator. Unfortunately, to date, the coatings for this concentrator have not been considered good enough to meet solar thermal propulsion requirements. It may, however, be good enough for power systems with lower intensity requirements. Additionally, SRS intends to produce more of these 5-m concentrators in the near future for another program. This represents an opportunity to test the use of this technology with high intensity photovoltaic technology.

Using concentrators designed for thermal power applications for illuminating photovoltaic arrays is not a new idea. We know of at least one proposal to utilize an antenna for power applications. This is the Inflatable Power Antenna [4]. What is new about this work is the availability of the 5-m antenna for testing.

OPTICAL MODEL OF INFLATABLE CONCENTRATOR

Inflatable concentrators for solar thermal propulsion are capable of producing hundreds of watts/cm^2. This is too much energy for any conventional materials used in photovoltaic arrays. However, the intensity can be tailored by positioning the photovoltaic cells at a distance from the focal plane of the concentrator.

Using this idea, we are trading the weight of the photovoltaic array with the weight of the inflatable concentrator. Inflatable concentrators are expected to weigh about 2 kg/m^2 in the near future and 1 kg/m^2 as support structures are improved. These weights include support struts, torus, inflation control system and pointing hardware. One square meter will collect about 1300 W in Earth orbit. Currently available photovoltaic arrays weigh about 5 kg/m^2, and technology advances should reduce this number by half. Reducing the surface area of the photovoltaic array can reduce the total weight of the power system. Total energy input is maintained by utilizing a large collector area. However, the weight of the inflatable collection area is about a factor of 2 lower than that of the photovoltaic array. The net result is a lower overall weight system.

PREDICTIONS OF INTENSITY AT SEVERAL LOCATIONS AWAY FROM THE FOCAL POINT

The question is then whether an inflatable concentrator can produce a useable intensity distribution. To answer this question we have calculated the intensity at 3 positions from the focal plane to give an idea of intensity profiles available for operation of photovoltaic arrays (see Fig. 15). The light focused by the concentrator lies roughly within an hourglass shape (only left half is shown). The waist of the hourglass lies at the focal plane and is very small with respect to the concentrator size. Therefore, the left half of the hourglass looks very much like a cone. The 3 positions chosen are 25 cm (Case 1), 50 cm (Case 2), and 75 cm (Case 3) from the focal plane towards the concentrator. The intensity is highest for Case 1 and lowest for Case 3.

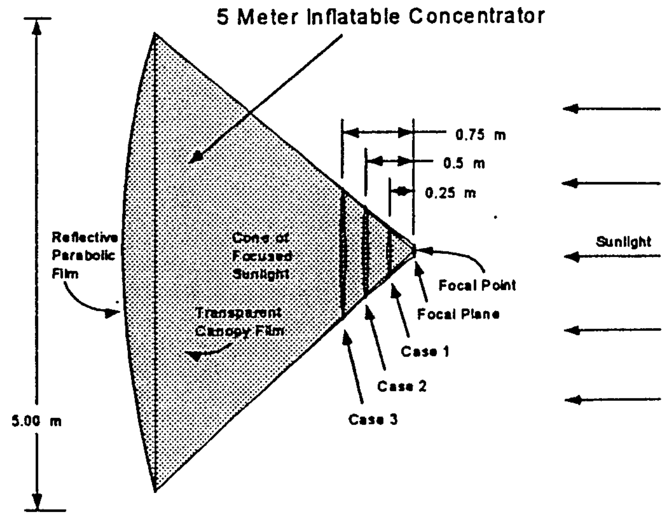

Figure 15. Optical Geometry of 5-m Concentrator Showing Positions of 3 Cases Studied

The numerical optical model used to make these calculations was originally written to determine the energy flux for off-axis concentrators [5]. The model includes slope errors (set to 3 mrad RMS), losses through the canopy and reflection losses at the reflective film. It does not yet include the ability to calculate intensity projected on a curved surface. It also does not include losses due to obstruction by the photovoltaic array (this is not an important feature for an off-axis code).

Figure 16 shows the radial profiles of intensity for the 3 cases. As expected, the intensity goes approximately as the square of the distance from the focal point. The intensity reaches its maximum at zero radius and decreases most slowly for Case 3. The array will have to be curved with the edge closest to the focal point if uniform intensity is required. For Case 3 the intensity peaks at about 13 suns; for Case 2, about 26 suns; for Case 1, about 105 suns.

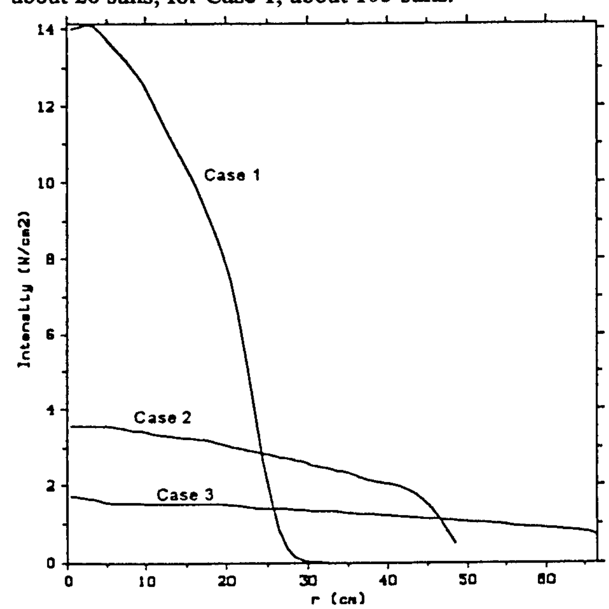

Figure 16. Radial Intensity Profiles for the 3 Cases Examined

Consider Case 2 as an example for a power system. The photovoltaic array would be circular with a diameter of 90 cm. The array would be dish shaped with an estimated ~15-cm depth to yield a flat intensity of about 3.5 W/cm^2. This depth is chosen because moving the edge 15 cm closer to the focal point will about double the intensity. The total power delivered to the array would be about 17 kilowatts. If the photovoltaic array weighs 5 kg (conservative for 0.65 m^2) and the concentrator system weighs 50 kg (assuming 2 kg/m^2), then the whole system would give 75 W/kg (assuming 25% efficient cells). This is a 25% improvement over using only a photovoltaic array.

There are some drawbacks to using an inflatable concentrator approach. It is not clear how long an inflatable concentrator can be kept inflated. Inherent leaks and leaks produced by space debris will require a constant make-up gas supply. Two to three month missions do not appear to be problem now, but a year or more is problematic. Low Earth orbit missions are also a problem because of unknown long-term effects of atomic oxygen on inflatable materials. Pointing requirements will also be more severe with a concentrator than for a flat panel solar array.

The leakage problem is being addressed through rigidization, "stop-leak" and "rip-stop" techniques. These approaches might add a weight penalty that won't be known until further research can be done.

There are two more advantages that might favor use of an inflatable concentrator. First, it may be easier to package an inflatable concentrator than a large photovoltaic array into an upper stage faring. Second, the concentrator might already be required for another function such as propulsion or power [4]. There may also be advantages for higher power systems than are currently used.

CONCLUSIONS

Inflatable structures have come a long way in the last 40 years. At the same time, many applications for these structures have yet to be tried. One of these applications is for concentrating sunlight on photovoltaic arrays. A 5-m antenna is available that could double as a concentrator to test this concept.

The calculations performed here indicate modest weight savings from using an inflatable concentrator with a photovoltaic array. A more detailed analysis is needed to determine if the advantages are truly substantial. For example, we need to find the optimal intensity for photovoltaics. We also need to include obstructions in the optical model or model an off-axis configuration. Are there special heat rejection requirements? Will the photovoltaics need to be heavier than assumed here? We propose that the space power community and the inflatable structure community work together to answer these questions and perhaps test a simple power system based on this 5-m antenna.

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